# Crack Minimization Model for Hot Weather Concreting

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**ABSTRACT**: This paper addresses fundamental issues of influence of elevated temperature and moderate wind speed on mass transport properties of concrete including moisture diffusivity D and convective moisture transfer coefficient $h_f$. Based on this data for concretes of varying water-cement ratios, certain invariant functional forms are postulated for variables of interest, leading to the development of a minimum crack mix design model.

## INTRODUCTION

Concrete structures in the harsh environment of the Gulf region in the Middle East suffer from deterioration or distress. As the damage propagates, a time comes when the safety and serviceability of the structure gets seriously impaired, hence necessitating repair work to restore safety and serviceability. In the Arabian Gulf region, the potentially aggressive environment has resulted in premature deterioration requiring extensive repairs. It is estimated that repair and maintenance of concrete structures in Saudi Arabia would run into billions in the coming few decades [1].

The single most important factor, which plays a dominant role in problem initiation, incubation and damage propagation period, is the movement of moisture in concrete. In a cementitious material saturated by liquid water, which is suddenly subjected to an ambient environment of lower relative humidity, an initial thermodynamic imbalance occurs between the external vapor concentration and that within the specimen. To restore thermodynamic equilibrium, the sample exchanges water vapor with the exterior through surface convection, resulting in diffusion of moisture from the core of concrete towards its exterior boundaries. The moisture diffusion process continues until a hygral equilibrium state is reached.

Air temperature, relative humidity and wind speed affect loss of moisture from the surface of concrete. ACI [123] discusses how the combination of these factors affects the evaporation rate. Higher drying shrinkage is to be expected with the increase in ambient temperature, decrease in relative humidity, and increase in air movement or wind speed around concrete and with the increase in the length of time for which concrete is exposed to drying conditions [2]. Initial cracking in concrete in most cases result from stresses due to restrained shrinkage on drying or the volume changes resulting from ambient and fresh concrete temperature variations. The focus of this work is on the material parameters that influence the moisture transport process in concrete.

Moisture diffusivity is the key physical parameter that is required for computation of moisture transport in cementitious materials. The transport coefficient is largely material specific, i.e. depends exclusively on material porosity, pore structure and moisture content. It is known that in the diffusion of gas through a catalyst, the diffusion paths are tortuous, irregularly shaped channels; accordingly, the flux becomes less than it would be in a uniform pore of the same length and mean radius. The effective coefficient of diffusivity in linear diffusion problems can be expressed in terms of a tortuosity parameter $\tau$, a factor that describes the relationship between the actual path-length relative to the nominal length of the porous media [3]. In lieu of measuring the tortuosity, diffusivity may be established as a regressed function of the water-cement ratio for cementitious materials. However, inasmuch as the diffusion of moisture through concrete is now known to be a non-linear problem, the influence of moisture concentration level on the diffusivity has also to be considered [4]. External influences like ambient temperature, humidity and wind speed are also believed to have an influence on the diffusivity coefficient and the convective surface transfer coefficient [5]. Water transport processes are often accompanied by temperature variation. From the thermodynamic theory, it should be expected that the transport properties increase with the temperature.

According to the Hirschfelder equation [6], for diffusion of a gas through a binary gas mixture, the diffusivity varies approximately in the ratio of absolute temperatures to the power 1.5. An application of this to concrete diffusivity has been recently noted by Jooss & Reinhardt [7].

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It is known that the modeling of stresses and damage associated with the restrained shrinkage of concrete cannot be established using constant values for the coefficient of diffusivity [8, 9]. The simulation of this problem can only be achieved by treating moisture diffusivity as a function of moisture concentration, which renders the boundary value problem non-linear. One feasible approach for this is to calibrate an assumed form for the coefficient of diffusivity in terms of unknown parameters of known functions of moisture concentration level, water-cement ratio and concrete temperature, using data from experiments and numerical results from a finite element driven program [10].

## GOVERNING EQUATIONS

The governing non-linear differential equation for moisture diffusion in the domain of a generalized 3-D solid in terms of the moisture content in the solid can be written as:

$$\frac{\partial C(x_k,t)}{\partial t} = \frac{\partial}{\partial x_i}\left[D(C)\frac{\partial C(x_k,t)}{\partial x_i}\right] \qquad \begin{matrix} k = 1,2,3 \\ i = 1,2,3 \end{matrix} \tag{1}$$

Where

$C = C\ (x_i,\ t)$ is the moisture content varying in domain and with time

$D(C)$ is the isotropic moisture diffusivity coefficient being function of C

Moisture diffusion at the boundary/surface of the solid is considered in the form of a convective boundary condition and can be written as:

$$D(C)\frac{\partial C(x_i,t)}{\partial x_i} n_i = h_f\,(C_e - C_s) \tag{2}$$

Where

$\frac{\partial C}{\partial x_i} n_i$ is the moisture gradient at the drying surface with a unit normal 'n'

$h_f$ is the surface factor or convective transfer coefficient

$C_s$ is the moisture content at the solid surface

$C_e$ is the moisture content/relative humidity of the ambience

A program DIANA-2D (Diffusion Analysis) written by Rahman [10] in FORTRAN is used to compute the moisture content history in a cementitious material due to moisture diffusion in the system. Owing to the dependence of diffusivity on moisture concentration and hence the non-linear nature of the problem, explicit analytical solution is not possible and such a model becomes necessary for the solution of the non-linear moisture diffusion equation.

The matrix differential equation governing moisture diffusion in any typical 2-D element in a finite element system and used in DIANA-2D is as follows:

$$\left[M_D\right]^e \{C\}^e + \left[V\right]^e \left\{\dot{C}\right\}^e + \left[M_s\right]^s \{C\}^s = \{F\}^e \tag{3}$$

Where

$\left[M_D\right]^e$ Element moisture diffusivity matrix

$\left[V\right]^e$ Moisture velocity matrix

$\{F\}^e$ Moisture loading vector

$\{C\}^e$ Nodal moisture content

$\left\{\dot{C}\right\}^e$ Nodal moisture content differentiated with respect to time

$[M_s]^s$ Moisture diffusivity matrix contribution from surface diffusion

$\{C\}^s$ Nodal moisture content of diffusing surface nodes

For 'N' denoting the element nodal shape functions, Ω representing the domain of the element and Γ showing the boundary of the element

$$[M_D]^e = \int_{\Omega_e} D(C)\left[\frac{\partial N^T}{\partial x}\frac{\partial N}{\partial x}\right] d\Omega_e \tag{4}$$

$$[V]^e = \int_{\Omega_e} N^T N d\Omega_e \tag{5}$$

$$[M_s]^s = h_f \int_{\Gamma} N^T N d\Gamma \tag{6}$$

$$\{F\}^e = h_f C_e \int_{\Gamma} N d\Gamma \tag{7}$$

The $[M_s]^s$ matrix is added at appropriate locations to the $[M_D]^e$ matrix to obtain the total element moisture diffusivity matrix $[M]^e$. eqn. 3 thus takes the final form:

$$[M]^e\{C\}^e + [V]^e\left\{\dot{C}\right\}^e = \{F\}^e \tag{8}$$

DIANA-2D solves eqn. 8 over the finite element domain to obtain nodal moisture content as a function of time. The transient nature of this equation is accounted for in the model by a step-by-step time integration scheme.

Weighted residual FEM in time domain is used to obtain the recurrence relationship for solving the transient moisture diffusion equation. To solve for unknown moisture content at any time $t_{i+1}$, in the finite element domain, the following relationship was obtained:

$$[A]\{C_{i+1}\} = [P]\{C_i\} + \{F^*\} \tag{9}$$

Where

$$[A]=[V]+[M]\theta\Delta t_i \tag{10}$$

$$[P]=[V]-(1-\theta)[M]\Delta t_i \tag{11}$$

$$\{F^*\}=\theta\{F_{i+1}\}\Delta t_i+(1-\theta)\{F_i\}\Delta t_i \tag{12}$$

Where θ is the controlling parameter, with its value depending on the type of finite difference scheme used for these time computations.

## PROCEDURE FOR COMPUTATION OF DIFFUSIVITY

A combined experimental-finite element based approach is used for computation of moisture diffusivity of the concrete mixes. The non-linear finite element model with least squares fit method (DIANA-2D) is employed for the computation of diffusivity parameters under varying temperatures and wind speeds. In this method, the parameter values are obtained by comparing the computed moisture profiles with the experimental drying/moisture loss data as a function of time.

Different investigators have used different mathematical forms for the dependence of coefficient of moisture diffusivity (D) on moisture content (C).Rahman [10] observed that the moisture loss ~ time curves for repair materials are steep at early ages, which correspond to the loss of water from large capillary pores and later the rate of moisture loss becomes extremely slow characterizing a low diffusivity of the materials. He incorporated the following functional form for diffusivity into **DIANA-2D**:

$$D(C)=b_0\ \tan(b_1 C^n) \tag{13}$$

Where $b_0$, $b_1$ and n are diffusivity parameters evaluated for best fit.

A typical plot of Equation 13 is shown in Fig. 1. Whilst the parameter $b_o$ is merely a measure of the amplitude of the diffusivity, parameters $b_1$ and $n$ control its shape. It is noted that higher values of the index $n$ result in a rapid decay of diffusivity $D$ versus moisture content, leading to lowered average values of $D$ ($D_{av}$).

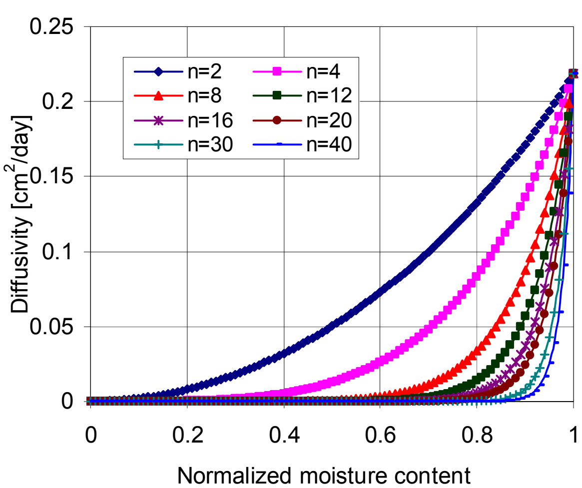


Figure 1. Generic shapes for diffusivity vs. moisture content.

The selected functional form and preliminary estimates of the parameters are incorporated in DIANA-2D. An iterative technique is then used to find the parameters that best fit the experimental data. This iterative technique involves computation of moisture loss over the domain of the experimental sample with appropriate boundary conditions followed by computation of the mean moisture loss in the sample. A residual or functional error is then computed using the following eqn.

$$Error = \sum_{t=0}^{ntime} \left[W_{ex}(t) - W_{fe}(t)\right]^2 \tag{14}$$

Where
$W_{ex}(t)$ is the mean experimental moisture loss at time $t$
$W_{fe}(t)$ is the mean moisture loss computed from finite element run

The values of the parameters for which the error in eqn. 14 is below a certain specified tolerance give the best fit. The parameters obtained by this procedure are then used to carry out finite element diffusion analysis on samples of different thickness to check the validity of the procedure.

## DRYING TESTS FOR DIFFUSIVITY COMPUTATIONS

Drying tests were conducted on sealed specimens of various thicknesses with unidirectional moisture movement to generate moisture loss evolution curves. These tests were carried out on three concrete mixes of water-cement ratio 0.45, 0.5 & 0.6 for a period of 8-12 weeks each, inside the environmental chambers. Relative humidity was maintained at 40% and exposure temperatures and wind speeds were varied as given in Table 1:

Table 1. Drying test regime for each concrete mix

| *Serial No.* | *Temperature ($^0C$)* | *Wind Speed (km/hr)* |
|---|---|---|
| 1 | 35 | 6 |
| 2 | 35 | 22 |
| 3 | 50 | 6 |
| 4 | 50 | 22 |
| 5 | 70 | 6 |
| 6 | 70 | 22 |

Concrete mix design was carried out following the ACI 211.1-91 specifications. A minimum water-cement ratio of 0.45 was selected so as to avoid the use of super-plasticizers or admixtures. Maximum aggregate size was selected as 3/8" depending on the minimum thickness of the diffusivity specimens being used. Aggregate grading was done according to ASTM C 33 specifications as 3/8" = 45%, 3/16" = 45% and 3/32" = 10%. All the coarse aggregates were properly washed to remove any fines or dust and then dried at room temperature for several weeks before use. The detailed mix design is given in Table 2:

Table 2. Concrete mix design

| *W/C* | *WATER $Kg/m^3$* | *CEMENT $Kg/m^3$* | *C.A $Kg/m^3$* | *F.A $Kg/m^3$* |
|---|---|---|---|---|
| 0.45 | 189 | 420 | 770.4 | 945 |
| 0.5 | 210.5 | 420 | 770.4 | 1003 |
| 0.6 | 252 | 420 | 770.4 | 788 |

Prismatic specimens of size 100x100xB (B = 25, 50, 75, 100 mm) were used for each case. All the specimens were cured in moulds for 24 hours sealed in plastic wraps. They were then demoulded and cured under wet burlap for 7 days. Specimens were then sealed with high temperature silicon and one layer of aluminum tape along the thickness to ensure moisture movement/diffusion in one dimension only. After this initial weight of each specimen was recorded and then transferred to the environmental chamber for drying. Specimens were weighed at suitable intervals during the whole exposure period to generate enough data points for setting up the moisture loss curves. Afterwards they were dried in an oven at 105$\pm$5 $^0$C to determine the evaporable moisture content in each case and hence generate the curves for moisture loss in percentage.

**BEST FIT DIFFUSIVITY LAW PARAMETERS**

Numerical computation of diffusivity law parameters ($b_0$, $b_1$ & n) and convective transfer coefficient ($h_f$) for each concrete mix under each exposure regime was carried out following the procedure described above. Finite element discretization of the diffusivity specimen is shown in Fig. 2:

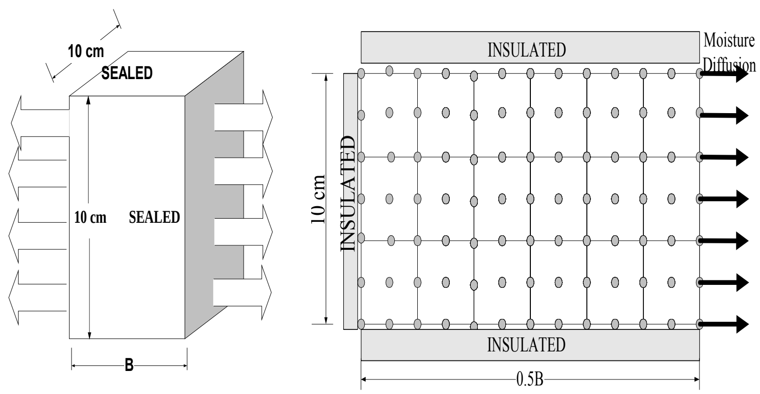


Figure 2. Finite element discretization of diffusivity specimen

Iterative runs were first carried out for the 100x100x75 mm specimen to ascertain the values of $b_0$, $b_1$, n & $h_f$., which best fit the experimental moisture loss (%) data. Later the computed parameter values were verified by running the model (DIANA-2D) for specimens of other thickness and fine-tuned. Good correlation was observed between the experimental and computed moisture loss data for the selected parameter values in each case, selectively shown in Figs. 3-8 for three mixes at 70 $^0$C and wind speed of 22 and 6 km/hr. The parameter values adopted for the best fits are given in Table 3.

Table 3. Parameters for diffusivity law of concrete, $D(C) = b_0 \tan (b_1 C^n)$

| W/C Ratio | Temp. ($^0$C) | Wind (km/hr) | $h_f$ (cm/day) | $b_0$ | $b_1$ | n | $D_{av}$ (cm$^2$/day) |
|---|---|---|---|---|---|---|---|
| 0.45 | 70 | 6 | 3.0 | 4.5 | 0.25 | 1.0 | 0.569 |
| 0.5 | 70 | 6 | 3.0 | 4.5 | 0.25 | 0.75 | 0.649 |
| 0.6 | 70 | 6 | 3.0 | 4.5 | 0.25 | 0.5 | 0.757 |
| 0.45 | 70 | 22 | 7.0 | 4.5 | 0.25 | 1.0 | 0.569 |
| 0.5 | 70 | 22 | 7.0 | 4.5 | 0.25 | 0.75 | 0.649 |
| 0.6 | 70 | 22 | 7.0 | 4.5 | 0.25 | 0.5 | 0.757 |
| 0.45 | 50 | 6 | 0.8 | 2.9 | 0.5 | 3.25 | 0.358 |
| 0.5 | 50 | 6 | 0.8 | 2.9 | 0.5 | 3.1 | 0.37 |
| 0.6 | 50 | 6 | 0.8 | 2.9 | 0.5 | 2.7 | 0.41 |
| 0.45 | 50 | 22 | 7.0 | 2.9 | 0.5 | 3.25 | 0.358 |
| 0.5 | 50 | 22 | 7.0 | 2.9 | 0.5 | 3.1 | 0.37 |
| 0.6 | 50 | 22 | 7.0 | 2.9 | 0.5 | 2.7 | 0.41 |
| 0.45 | 35 | 6 | 0.8 | 1.35 | 1.0 | 9.25 | 0.162 |
| 0.5 | 35 | 6 | 0.8 | 1.35 | 1.0 | 6.5 | 0.218 |
| 0.6 | 35 | 6 | 0.8 | 1.35 | 1.0 | 5.3 | 0.258 |
| 0.45 | 35 | 22 | 7.0 | 1.35 | 1.0 | 9.25 | 0.162 |
| 0.5 | 35 | 22 | 7.0 | 1.35 | 1.0 | 6.5 | 0.218 |
| 0.6 | 35 | 22 | 7.0 | 1.35 | 1.0 | 5.3 | 0.258 |

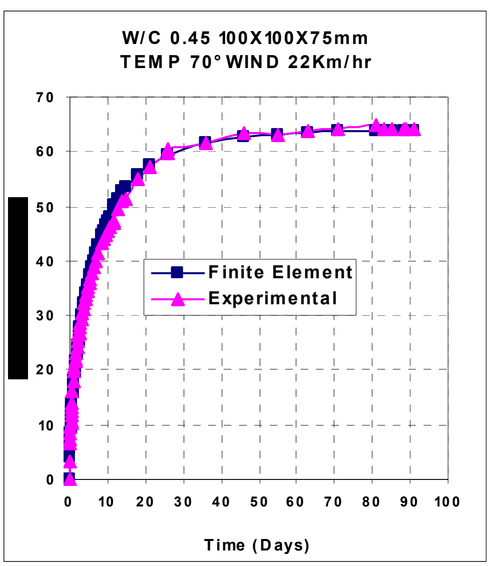


Figure 3. Moisture loss curves for w/c = 0.45 at 70 $^0$C & 22 km/hr wind

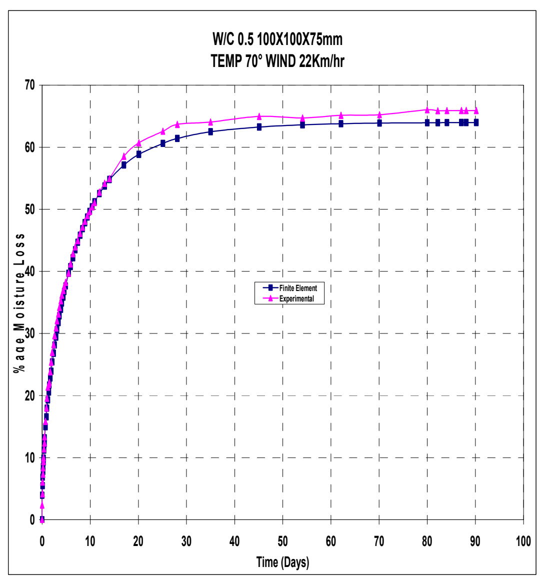


Figure 4. Moisture loss curves for w/c = 0. 5 at 70 $^0$C & 22 km/hr wind

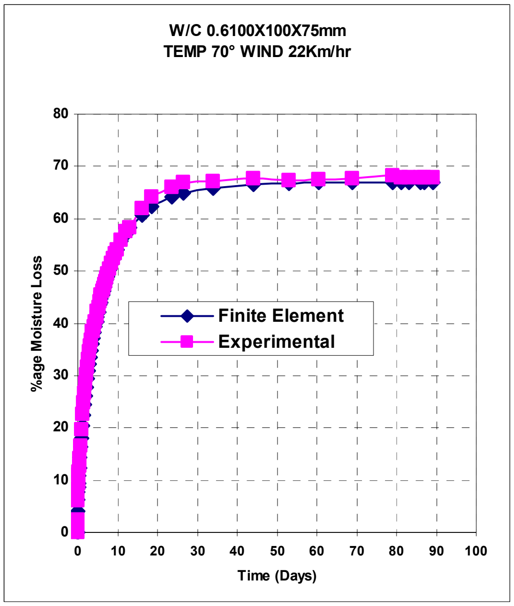


Figure 5. Moisture loss curves for w/c = 0.6 at 70 $^{0}$C & 22 km/hr wind

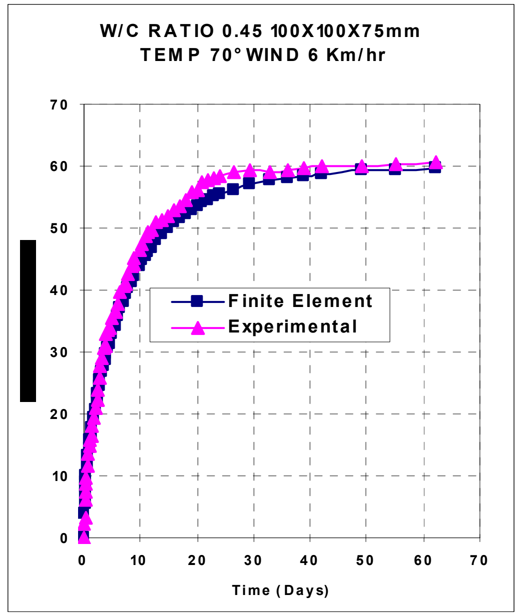


Figure 6. Moisture loss curves for w/c = 0.45 at 70 $^{0}$C & 6 km/hr wind

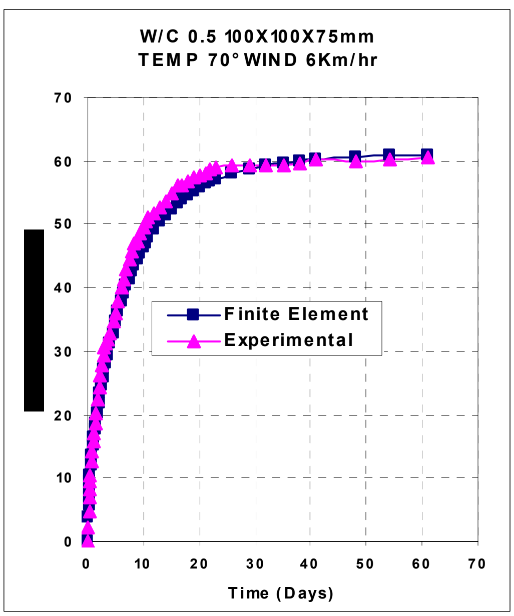


Figure 7. Moisture loss curves for w/c = 0. 5 at 70 $^{0}$C & 6 km/hr wind

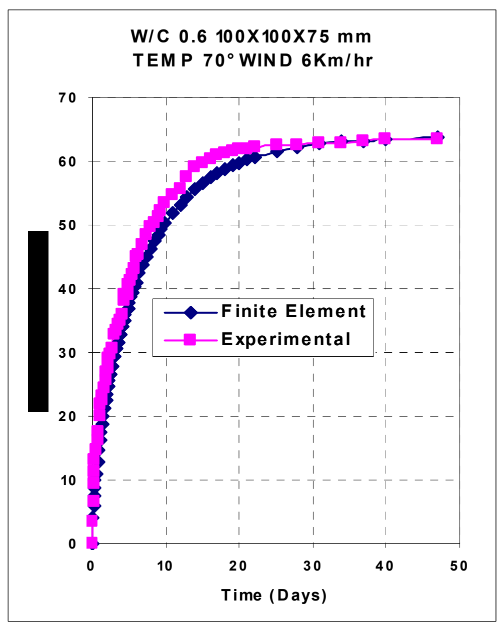


Figure 8. Moisture loss curves for w/c = 0.6 at 70 $^{0}$C & 6 km/hr wind

## RELATIVE MAGNIFICATION OF DIFFUSIVITY DUE TO TEMPERATURE INCREASE

Figs. 9-11 show the effect of ambient temperature on diffusivity plotted as a function of normalized moisture content. A significant increase in moisture diffusivity can be observed with the increase in temperature from 35-70 $^0$C for each concrete mix. The effect is incorporated in the diffusivity law by using a higher value of $b_0$ and a lower value of $b_1$ & n at higher temperature. Increase in moisture diffusivity of concrete with the rising temperature is due to increase in the energy of the water vapor molecules and thermal dilation of pores. Also applying the Kelvin Thomson equation of thermodynamics, relative humidity of pores should increase with the increase in ambient temperature. This promotes transport in the form of liquid water rather than water vapors, which is the more efficient transport mechanism [7].

The regressed relationship between average diffusivity at 50 $^0$C and 35 $^0$C, at 70 $^0$C and 50 $^0$C and 70 $^0$C and 35 $^0$C are found to be best expressed in the exponential forms given by

$$(D_{av})^{70} = 0.0953(\exp)^{5.0767*(D_{av})50} \qquad (15a)$$

$$(D_{av})^{70} = 0.3504(\exp)^{2.9337*(D_{av})35} \qquad (15b)$$

$$(D_{av})^{50} = 0.2836(\exp)^{1.36*(D_{av})35} \qquad (15c)$$

where

$(D_{av})^{70}$ is the average moisture diffusivity of concrete at 70 $^0$C (cm$^2$/day)
$(D_{av})^{50}$ is the average moisture diffusivity of concrete at 50 $^0$C (cm$^2$/day)
$(D_{av})^{35}$ is the average moisture diffusivity of concrete at 35 $^0$C (cm$^2$/day)

A typical plot depicting form expressed by equation (15c) is shown in Fig.12.

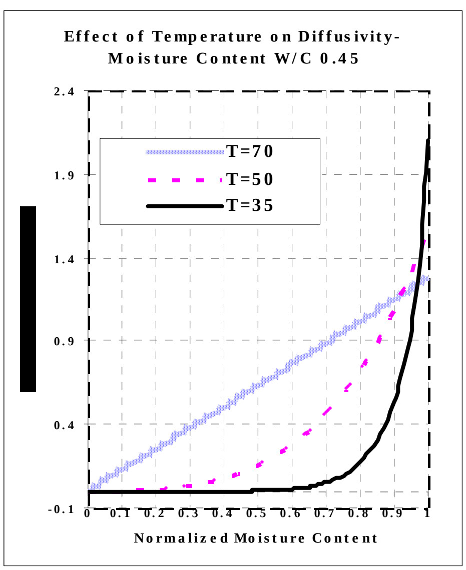


Figure 9. Effect of temperature on diffusivity of concrete of w/c = 0.45

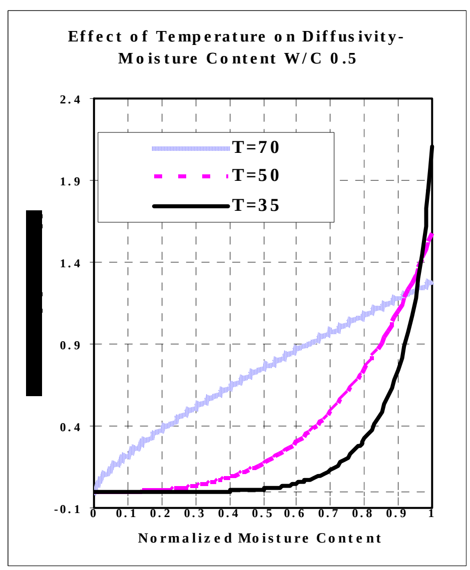


Figure 10. Effect of temperature on diffusivity of concrete of w/c = 0.5

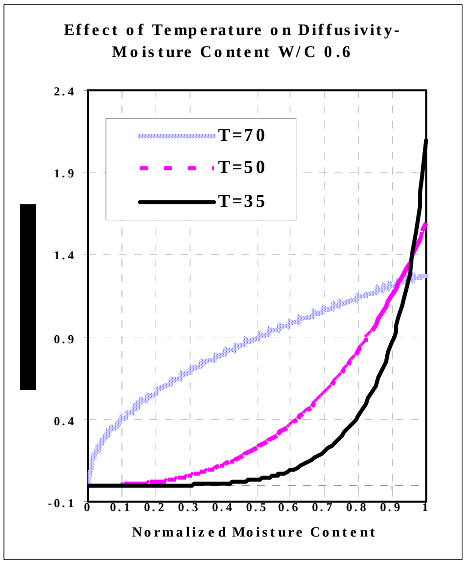


Figure 11. Effect of temperature on diffusivity of concrete of w/c = 0.6

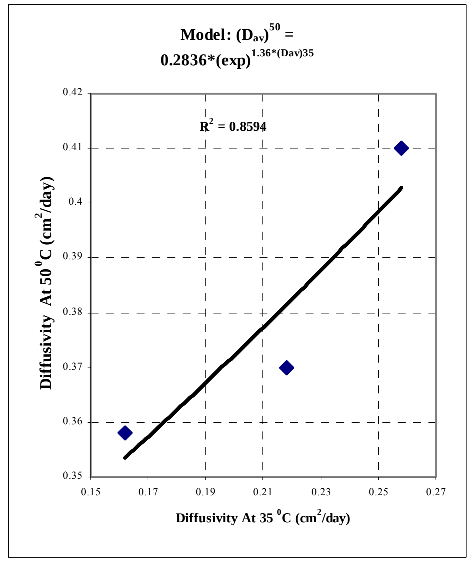


Figure 12. Relative Magnification of Diffusivity at (50 $^0$C / 35 $^0$C)

## EXPLICIT FORM OF DIFFUSIVITY AS FUNCTION OF WATER-CEMENT RATIO AND TEMPERATURE

Figs. 13-15 show the effect of water-cement ratio on diffusivity versus normalized moisture content. It can be seen that diffusivity of concrete increases with the increase in water-cement ratio of the mix. The effect is accounted for in the diffusivity law by varying the value of parameter ‘n’, with the value being lower at higher water-cement ratio. This phenomenon can be attributed to the increase in porosity and connectivity of pores in the hydrated cement paste and hence the decreased tortuosity of diffusion paths at higher water-cement ratio. Also the excess water reduces the amount of cement grains present around the aggregate surfaces and thus results in an increased porosity of the interfacial zone. Thus the moisture gets more and continuous space and hence diffuses with a greater ease.

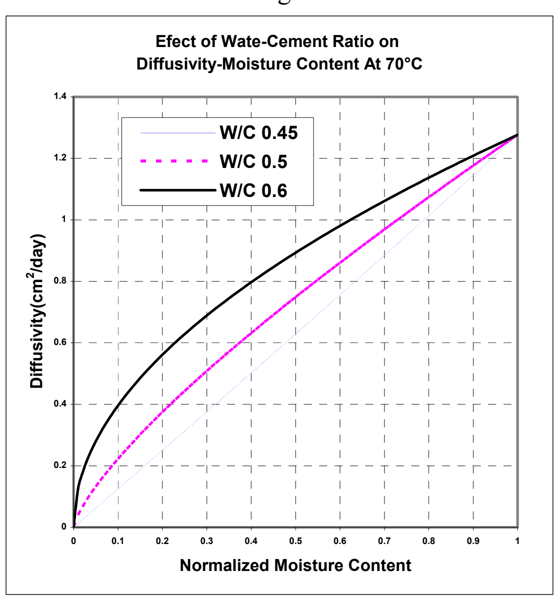


Figure 13. Effect of w/c ratio on diffusivity of concrete at 70 $^0$C

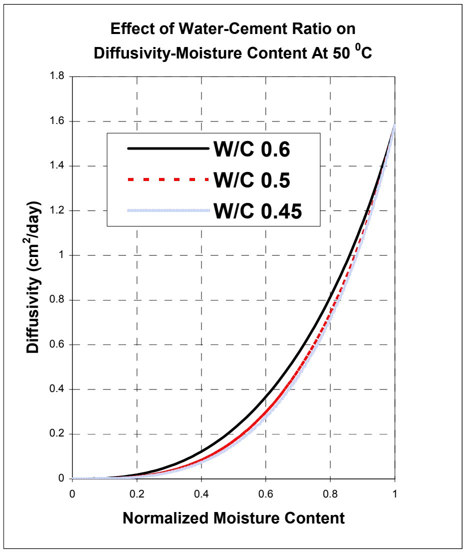


Figure 14. Effect of w/c ratio on diffusivity of concrete at 50$^0$C

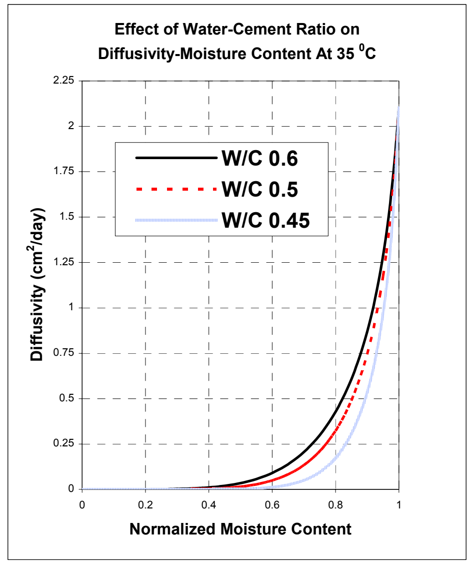


Figure 15. Effect of w/c ratio on diffusivity of concrete at 35 $^0$C

Average moisture diffusivity of ordinary concrete ($D_{av}$) at 35 $^0$C, 50 $^0$C and 70 $^0$C can be predicted from the water-cement ratio of the mix, by the following general equation:

$$(D_{av})^T = A(T)*(w/c)+B(T) \tag{16}$$

A typical regressed plot is shown in Fig. 16. At an ambient temperature of 35 $^0$C the value of 'A' is found to be 0.6057 & 'B' as –0.1003, at 50 $^0$C the value of 'A' as 0.3543 & 'B' as 0.1963 and at 70 $^0$C the value of 'A' as 1.3714 & 'B' as 0.0234.

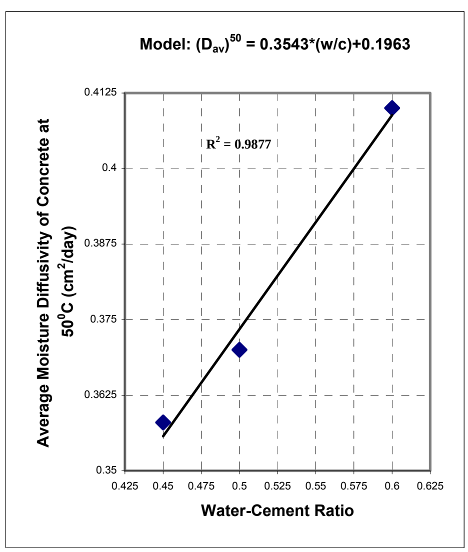


Figure 16. Average diffusivity at 50 $^0$C ~ w/c ratio of concrete

## MINIMUM CRACK MIX DESIGN MODEL

Regressing the data obtained for moisture diffusivity and shrinkage strains in concrete (recorded under similar exposures), a new approach to concrete mix design (w/c ratio) for crack free concrete under hot weather conditions is presented in the following paragraphs.

Fig. 17 shows the regressed relationship between mean moisture loss (%) in concrete at 28 days of exposure $(\text{mlp})^{28}$ for the specimen size of 100x100x75 mm and the shrinkage strains at 45 days $(\varepsilon_{sh})^{45}$ measured in a standard 75x75x300mm ASTM specimen. Each point on this curve corresponds to a particular concrete mix (w/c ratio) for a particular exposure temperature and wind speed at 40 % R.H. The relationship is found to be:

$$(\varepsilon_{sh})^{45} = 281.23(\exp)^{0.011*(mlp)28} * 10^{-6} \tag{17}$$

eqn. 17 is an invariant relationship in general between $\varepsilon_{sh}$ $(t=t_1)$ and mlp $(t=t_2)$, and is independent of other variables. Time $t_1$ and $t_2$ may be taken to be the same or different, depending upon target objectives.

Based upon a threshold value of 400 μs for shrinkage strain at 45 days to ensure crack free concrete, the mean moisture loss in percentage at 28 days, $(\text{mlp})^{28}$, for a specimen size of 100x100x75 mm should not be greater than 32 %, as obtained by eqn.17.

Next the data is regressed for $\text{mlp}^{28}$ as a function of average moisture diffusivity of concrete $D_{av}$(cm$^2$/day) and ambient wind speed 'ω' (Km/hr) for the specimen size of 100x100x75 mm, as shown in Fig. 28. The regression model obtained is as follows:

$$(\text{mlp})^{28} = 14.1111+68.091*(\text{D}_{\text{av}})+0.2443*(\omega) \tag{18}$$

It may be noted that the moisture loss percentage is postulated to be an invariant relationship of the form

$$\text{mlp} = \text{mlp}(\text{D}_{\text{av}}, \omega, RH, t) \tag{19}$$

The data used in this work has fixed the RH at a relatively conservative 40% and the time t for mlp output as 28 days. From the value of $(\text{mlp})^{28}$ obtained from eqn. 17 and using the ambient wind speed to which the concrete is to be exposed in practice, the required average moisture diffusivity of concrete can be obtained using eqn. 18.

Fig. 18 shows the regressed relationship for $D_{av}$ as a function of ambient temperature T ($^0$C) and water-cement ratio (w/c) of the concrete mix. The model adopted for this relationship is as under:

$$(\text{D}_{\text{av}}) = -0.6214+0.7295*(\text{w/c})+0.0128*(\text{T}) \tag{20}$$

Eqn. 20 is the third of the invariant relations proposed in this model, in which other mix design parameters such as aggregate to cement ratio (a/c) and curing time could be incorporated.

From the value of $D_{av}$ obtained from eqn. 18 and the ambient temperature to which the concrete is to be exposed, the required water cement ratio of the mix can be calculated using eqn. 20.

The above-mentioned procedure for concrete mix design can be explained by solving an example. For a crack free concrete $(\varepsilon_{sh})^{45}$ is limited to 400 μs, which corresponds to an $(\text{mlp})^{28}$ value of 32 % as obtained from eqn. 17. Using this value of $\text{mlp}^{28}$ and taking a value of say 12 Km/hr for the exposure wind speed, required $D_{av}$ for the concrete mix as calculated by eqn. 18 comes out to be 0.237 cm$^2$/day. From eqn. 20, using this value of $D_{av}$ and a value of say 40 $^0$C for the ambient temperature, the required water cement ratio for the concrete mix is calculated as 0.45.

Following this procedure for concrete mix design within the specified limits of ambient temperature T($^0$C) and wind speed ω(Km/hr), data was generated to regress water cement ratio (w/c) of the concrete mix as a direct function of T and ω. The best-fit plot is shown in Fig. 19 and the model obtained is given in the following equation:

$$(w/c) = 1.2522\text{-}0.0175^*(T)\text{-}0.0049^*(\omega) \qquad (21)$$

This model can now be used to directly calculate the required water cement ratio for a minimum crack concrete mix design for given exposure conditions of ambient temperature and wind speed prevalent in relatively dry and hot weather conditions.

Some of the predictions for w/c based on this model yield interesting results. If one sets T = 35 $^0$C and $\omega$=5km/hr, one obtains w/c = 0.61 which may be surmised as being somewhat on the wet side. This may be interpreted from the data of Fig. 17 which shows that at T = 35 $^0$C, only the w/c = 0.6 just reached the threshold strain of $(\varepsilon_{sh})^{45}$ = 400 μs, with the other two mixes yielding lower 45-day strain values. In this case, if one was to use a more stringent criterion of $(\varepsilon_{sh})^{45}$ = 375 μs, the set of eqns. 17, 18 and 20 would yield a w/c = 0.43 for T = 35 $^0$C and $\omega$=5km/hr.

On the higher side of temperatures at no wind (T ≥ 60 $^0$C, $\omega$=0), the w/c predicted is ≤ 0.20. This is too dry a mix, even in the presence of new generation plasticizers. Fig. 17 shows that at this high range of temperature, $(mlp)^{28}$ is ≥ 45% for all mixes tested. Thus to design a mix for an $(mlp)^{28}$ = 32% that corresponds to $(\varepsilon_{sh})^{45}$ = 400 μs requires the use of a significantly lower w/c. For such a case, one could use a more relaxed $(\varepsilon_{sh})^{45}$ criterion. As an upper limit, with $(\varepsilon_{sh})^{45}$ = 450 μs, the model yields a w/c = 0.36 for T = 60 $^0$C and $\omega$=0. The model is noted to be quite sensitive to the chosen criterion of $(\varepsilon_{sh})^{45}$.

With the model depicted in its final form by eqn. 20, one can set limits on exposure environment as

$$\begin{aligned} &35 \le T \le 50 \qquad (^\circ C) \\ &0 \le \omega \le 22 \qquad (km/hr) \end{aligned} \qquad (22)$$

and a concrete curing time of seven days. Should w/c from strength requirements be lower than that predicted by eqn. 21 (as for lower range T), then the strength criterion for w/c determination would obviously govern.

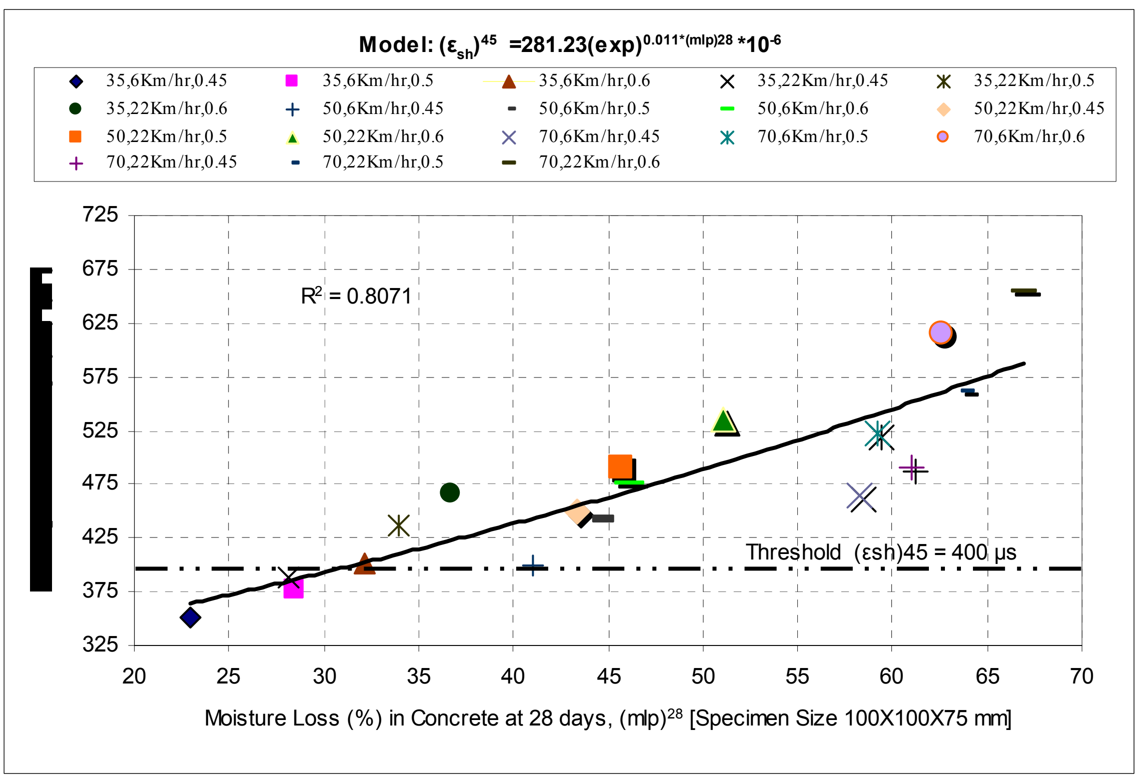


Figure 17. Moisture loss at 28 days versus $\varepsilon_{sh}$ at 45 days

**Model:**

$$(mlp)^{28} = 14.1111+68.091*(D_{av})+0.2443*(\omega)$$

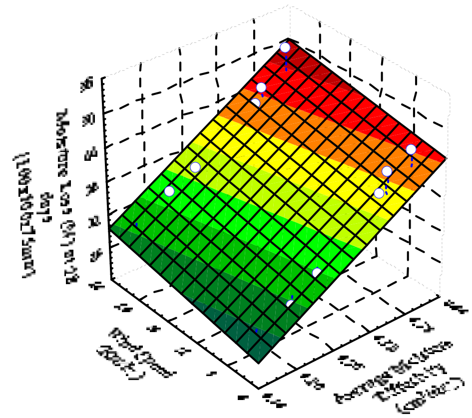

Figure 18. Surface of $(mlp)^{28}$ in terms of $D_{av}$ and $\omega$

**Model:**

$$(D_{av}) = -0.6214+0.7295*(w/c)+0.0128*(T)$$

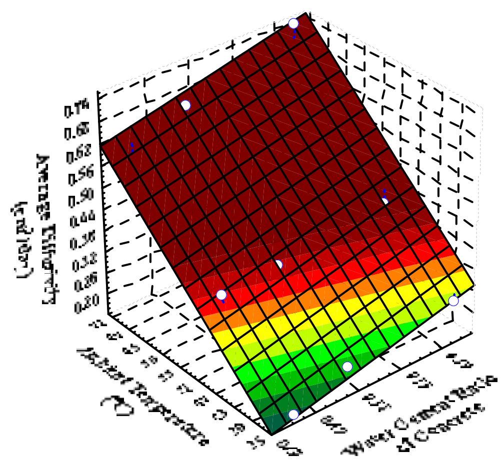

Figure 19. Surface of $D_{av}$ as a function of w/c and T

**Model:**

**$(w/c) = 1.2522-0.0175*(T)-0.0049*(\omega)$**

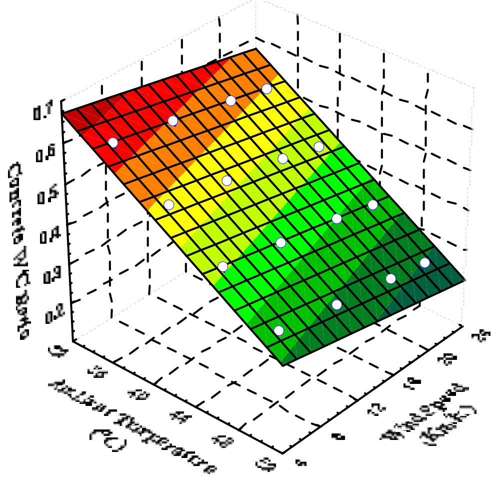

Figure 20. Surface determining w/c in terms of T and ω

## CONCLUSIONS

An user friendly model has been derived that can be used to design a concrete mix in terms of the water-cement ratio w/c so as to meet a minimum crack criterion that can be selected by the user for hot-weather conditions. Detailed equations for the model are presented using a 45-day threshold free shrinkage strain criterion $(\varepsilon_{sh})^{45} \leq 400$ μs.

Based on $(\varepsilon_{sh})^{45} \leq 400$ μs criterion, the model yielding w/c in terms of exposure defined by T ($^0$C) and wind speed ω (km/hr) is restricted to the conditions

$$35 \leq T \leq 50 \qquad (°C)$$

$$0 \leq \omega \leq 22 \qquad (km/hr)$$

for concrete cured for seven days. For temperature somewhat lower than 35 $^0$C, it is shown that a stricter criterion of $(\varepsilon_{sh})^{45} = 375$ μs is advisable in order to obtain w/c values more in range of w/c chosen from strength requirements. In contrast, for T > 50 $^0$C, the criterion needs to be relaxed to $(\varepsilon_{sh})^{45} = 450$ μs in order to obtain mixes that would otherwise simply not be workable.


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